APPENDIX F
HYDRAULICS OF BAFFLES

F. HYDRAULICS OF BAFLES

F.1. Fish-Passage and Culvert-Capacity Hydraulic Analysis

NOTE: The material presented in the remainder of this chapter is extracted from the *Design of Road Culverts for Fish Passage* (WDFW 2003). It is intended to serve as a convenient reference or starting point for subsequent efforts to revise and improve it for Caltrans use.

The velocity of flow associated with culvert baffle systems can be derived from hydraulic laboratory work conducted by several groups. N. Rajaratnam and C. Katopodis (1989 and 1990) studied various combinations of baffle geometries, heights, spacings, slopes and flows in models of circular culverts. Hydraulic-model studies for weir baffles in box culverts were studied by Shoemaker (1956). These models can be used for both the fish-passage velocity and culvert-capacity analyses. Rajaratnam and Katopodis developed flow equations for all the styles they tested. Those equations are simplified here to the form of Equation 1.

$$Q = C\left(\frac{y_0}{\mathrm{D}}\right)^a \left(gS_0\mathrm{D}^5\right)^{1/2}$$

Equation 1

Where:

C = coefficient that depends on the baffle configuration

D = diameter of the culvert

a = exponent that depends on the baffle configuration

Q = discharge in cfs

y_o = depth of water

g = gravitational acceleration in ft/sec/sec

S_o = nondimensional slope of the culvert

Z_o = height of the baffle (as shown in Figure F-1)

The dimensions and their respective coefficients and exponents for Equation 1 are shown in Table F-1. The first column contains the labels of experimental baffles that were provided by the authors; data for those without labels have been extrapolated. The difference in styles are represented by the dimensions in the next two columns; Z_o is the average height of the baffle, L is the spacing between baffles and D is the diameter of the culvert. The limits shown in the table are the limits of experimental data or valid correlation for the coefficients and exponents.

Baffle Hydraulics

	Z_o	L	C	a	Limits
WB-2	0.15D	0.6D	5.4	2.43	0.25 y0/D < 0.8
WB-1	0.15D	1.2D	6.6	2.62	0.35 y0/D < 0.8

	Z_o	L	*C*	*a*	Limits
	0.15D	2.4D	8.5	3.0	
WB-3	0.10D	0.6D	8.6	2.53	0.35 y0/D < 0.8
WB-4	0.10D	1.2D	9.0	2.36	0.20 y0/D < 0.8
	0.10D	2.4D	9.6	2.5	

WB = Weir/Baffle Style

Using Equation 1, calculate the depth of flow. The resulting velocity is the flow divided by the cross-section flow area between the baffles.

The weir baffles studied by Rajaratnam an Katopodis (1989 and 1990) were actually horizontal weirs, rather than sloping baffles as shown in Figure F-1. This is the most reliable information available for predicting the roughness of baffles recommended in this guideline and must be used with sound judgment. Box culverts were not included in this study. The models presented below for culvert capacity with baffles can be used for fish-passage analysis in box culverts.

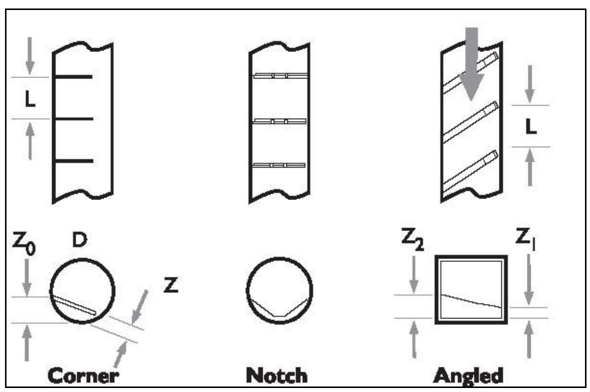

Figure F-1. Common Baffle Styles

Recommended styles of baffles for round and box culverts.

Hydraulic model studies for weir baffles in square box culverts were studied by Shoemaker (1956). Internal-culvert friction loss and entrance losses were calculated from hydraulic model studies. Shoemaker used the Darcy-Weisbach friction equation (Equation 2) as a hypothetical model for culverts with baffles:

$$HW = \frac{\left(\mathrm{K}_e + \mathrm{C}_e + \frac{fL_c}{D}\right)\mathrm{V}^2}{2g} + \mathrm{P} - S_0 L_c$$

Equation 2

Where:

f = the friction coefficient

L_c = the length of the culvert

D = the diameter of pipe (four times the hydraulic radius of noncircular pipes)

$\frac{V^2}{2g}$ = the gross section velocity head in the culvert where V is the average velocity in ft/sec

P = the outlet water-surface elevation

S_o = the slope of the culvert

K_e = culvert entrance head-loss coefficient

C_e = culvert exit head-loss coefficient

The baffles tested were full-width, level baffles with rounded leading edges at a radius equal to one tenth of the culvert height. Baffle heights of 0.10, 0.20 and 0.30 times the culvert height and spacings of 1.0, 2.0 and 4.0 times the culvert height were studied.

Shoemaker's variation of the Darcy-Weisbach friction factor is depicted in Figure F-2, where *Z* is the baffle depth and *L* is the baffle spacing.

Friction factors for short baffle spacings should be used cautiously. As would be expected, as the baffle spacing approaches zero, the baffle roughness actually decreases and the effective cross-sectional area of the culvert becomes the area of the culvert remaining above the baffles. Shoemaker, in his calculation of velocity head, used the gross culvert area.

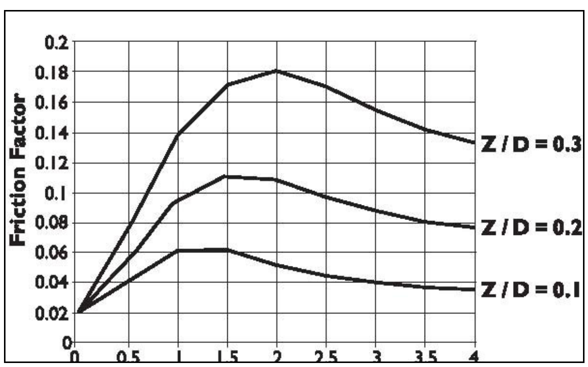

Figure F-2. Variation of Darcy Weisbach Friction Factor with Baffle Spacing

A second analysis by Shoemaker (1956) is intended specifically for estimating culvert capacity. It provides a means for evaluating other energy components making up the hydraulic grade line through a culvert. Shoemaker made the assumption that entrance, outlet and friction losses are proportional to the velocity head. With these assumptions, the energy equation for flow through the culvert can be written using Equation 2, where *HW* is the headwater elevation above the invert at the culvert entrance. Other parameters are as previously defined. Shoemaker (1956) describes a reasonable approximation of *P* as the distance from the culvert invert to the center of the flow in the opening above a baffle.

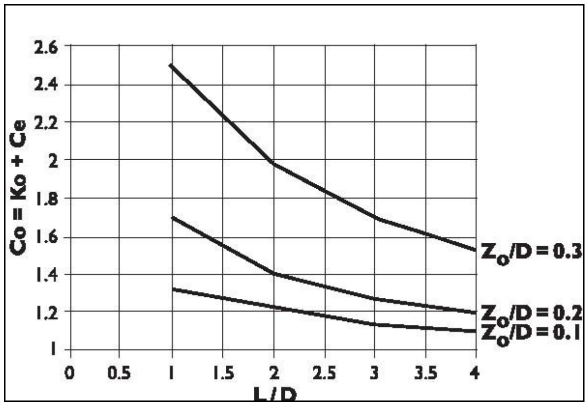

Figure F-3. Energy Coefficients for Various Baffle Arrangements

Shoemaker (1956) derived the combined values of the head loss coefficients *Ke* and *Ce* as a single coefficient, *Ca,* which is shown in Figure F-3 as a function of baffle spacing and height. In Shoemaker's model, the culvert entrance and exit had aprons extending 2.5 times the culvert width, with wing walls flaring at 34 degrees from the culvert line, mitered at a 2:1 slope. The baffle that was furthest upstream was consistently placed one culvert height downstream from the culvert entrance and the downstream-most baffle was placed at the edge of the apron.

As an alternative to the baffle analysis presented above, the fish baffles or weirs can be analyzed as a sharp-crested or broad-crested weir using equations from the FHWA HEC-22 publication, Urban Drainage Design Manual. The equations are listed below:

Sharp Crested Weir

$$Q = C_{SCW} L H^{1.5}$$

Where: Q = discharge in cfs

L = Horizontal weir length in ft

H = head above weir crest excluding velocity head in ft

$$C_{SCW} = \left(3.27 + 0.4\left(\frac{H}{H_C}\right)\right)$$

H_C = height of weir in ft

When the tailwater just below the weir rises above the weir crest elevation, the weir will be submerged and the resulting discharge equation is:

$$Q_s = Q_r \left(1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right)^{0.385}$$

Where: Q_s = submerged flow in cfs

Q_r = unbmerged weir flow using above equation in cfs

H_1 = upstream head above crest in ft

H_2 = downstream head above crest in ft

Broad-Crested Weir

$$Q = C_{BCW} L H^{1.5}$$

Where: Q = discharge in cfs

C_{CBW} = broad-crested weir coefficient (2.34 – 3.32)

L = broad-crested weir length in ft

H = head above weir crest in ft

See Table F-2 for C Values as a function of weir crest breadth and head.

Broad-Crested Weir Coefficient C Values as a Function of Weir Crest

Broad-Crested Weir Coefficient C Values as a function of Weir Crest Breadth and Head (coefficient has units of $ft^{0.5}$/sec).											
Head (ft)	Breadth of Crest of Weir (ft)										
	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	10.00	15.00
0.2	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
0.4	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
0.6	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
0.8	3.30	3.04	2.85	2.68	5.60	2.60	2.678	2.68	2.68	2.69	2.64
1.0	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
1.2	3.32	3.20	3.08	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
1.4	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
1.6	3.32	3.29	3.28	3.07	2.89	2.75	0.68	2.66	2.65	2.64	2.63
1.8	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
2.0	3.32	3.31	3.30	3.03	2.85	2.76	2.72	2.68	2.65	2.64	2.63
2.5	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
3.0	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
3.5	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
4.0	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
4.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
5.0	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
5.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

F.2. References

Rajaratnam, N. 1989. Hydraulics of culvert fishways III: slotted-weir culvert fishways. Canadian Journal of Civil Engineering. 16:3:375-383.

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